Massive Gravitons and Dark Matter

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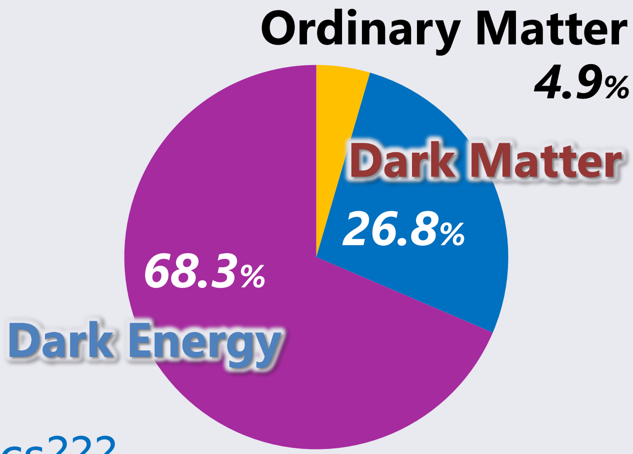
KA and S. Mukohyama, arXiv: 1604.06704,
KA and K. Maeda, arXiv: 1707.05003,

Introduction

What is dark matter??



We should need beyond standard model!!

Beyond SM of particle physics?

Beyond SM of gravity?

DM candidates in beyond SM of particle physics???

→ WIMPs, Axion and other many candidates…

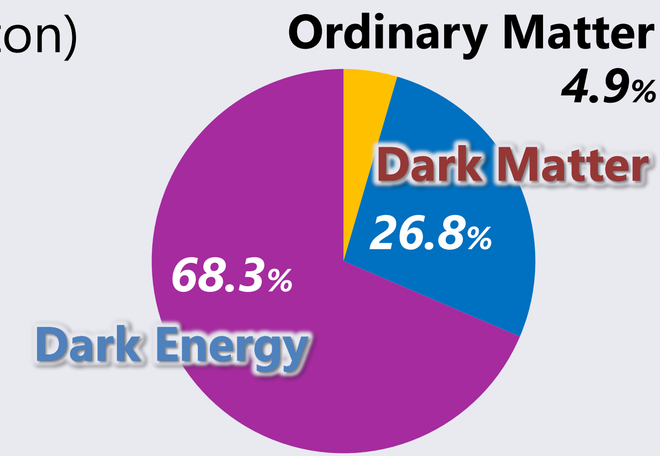
Some simple models are excluded by experimental null results.

DM with only gravitational interactions??? (DM from gravity sector?)

Interactions are definitely Planck suppressed.

Introduction

GR is a theory of massless spin-2 field (graviton)



What is graviton?

- It should be spin-2 field (+other dof?)
- Massless field or Massive field?
- How many gravitons?

There could be several gravitons as other gauge bosons.

For simplicity, we focus on the case of two gravitons

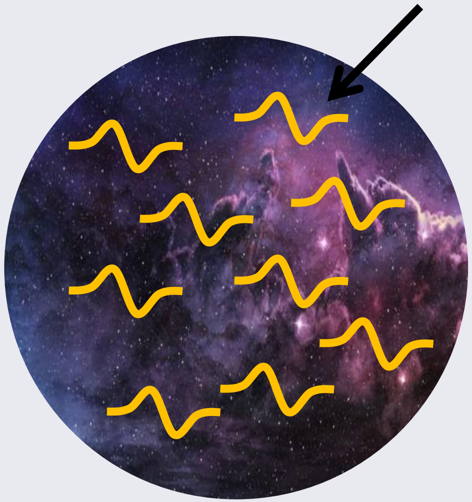
→ Bigravity = massless graviton and massive graviton

Massive graviton is a candidate of DM

Massive gravitons as dark matter

Massive graviton = Massive spin-2 field

Spacetime "fluctuation" is DM



Spacetime "deformation" is DM

Stochastic massive gravitons
= particle dark matter

KA and S. Mukohyama, arXiv: 1604.06704.

Massive graviton condensate
= field dark matter

KA and K. Maeda, arXiv: 1707.05003.

Non-linear bigravity theory

Two dynamical metrics: $g_{\mu\nu}$ and $f_{\mu\nu}$ (Hassan, and Rosen, 2011)

$$S = \frac{1}{2\kappa_g^2}\int d^4x\sqrt{-g}R(g) + \frac{1}{2\kappa_f^2}\int d^4x\sqrt{-f}\mathcal{R}(f) + S_{\rm int}(g,f) + S^{[\rm m]}$$

The interaction terms are given by dRGT form (ghost-free).

de Rham, Gabadadze, and Tolley (2011)

For a while, we ignore the matter action $S^{[\rm m]}$.

What we want to calculate?

Gravitons propagating on background

$$g_{\mu\nu} = g_{\mu\nu}^{\rm background} + \delta g_{\mu\nu}^{\rm perturbation}$$
$$f_{\mu\nu} = f_{\mu\nu}^{\rm background} + \delta f_{\mu\nu}^{\rm perturbation}$$

Backreaction from gravitons

High frequency approximation

In general, there is no way to decompose
``background`` and ``perturbations`` if backreaction is included.

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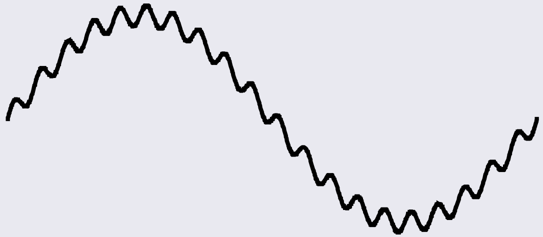
Backreaction from gravitons

However, they can be decomposed when perturbations are high-frequency.

(Isaacson, 1968)



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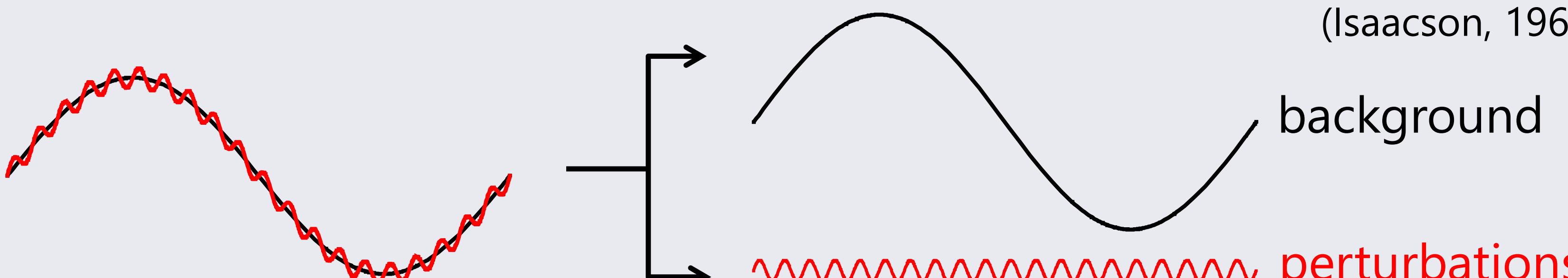


Graviton $T^{\mu\nu}$ in Bigravity

Assuming $\partial^2 \overset{(0)}{g} \ll m^2$, we find the Einstein and Klein-Gordon equations

$$G^{\mu\nu}[\overset{(0)}{g}] \simeq \frac{1}{M_{\rm pl}^2}(\langle T^{\mu\nu}_{\rm gw}\rangle_{\rm low} + \langle T^{\mu\nu}_{G}\rangle_{\rm low})$$

$$\Box h_{\mu\nu} \simeq 0\,, \quad (\Box - m^2)\varphi_{\mu\nu} \simeq 0 \qquad \text{+ TT conditions}$$

where $T^{\mu\nu}_{\rm gw} \sim (\partial h_{\mu\nu})^2\,, \quad T^{\mu\nu}_{G} \sim (\partial\varphi_{\mu\nu})^2 + m^2\varphi_{\mu\nu}^2$

The metrics are given by

$$g_{\mu\nu} \simeq \overset{(0)}{g}_{\mu\nu} + \frac{h_{\mu\nu}}{M_{\rm pl}} + \frac{\varphi_{\mu\nu}}{M_G}\,, \quad f_{\mu\nu} \simeq \overset{(0)}{g}_{\mu\nu} + \frac{h_{\mu\nu}}{M_{\rm pl}} - \frac{\varphi_{\mu\nu}}{\alpha M_G}\,,$$

$(\alpha = M_{\rm pl}^2/M_G^2)$

Matter coupling?

Minimal way: $S^{[\rm m]} = S^{[\rm m]}(\psi, g) \;\to\; \frac{1}{2M_{\rm pl}} h_{\mu\nu}T^{\mu\nu}_{\rm m} + \frac{1}{2M_G}\varphi_{\mu\nu}T^{\mu\nu}_{\rm m}$

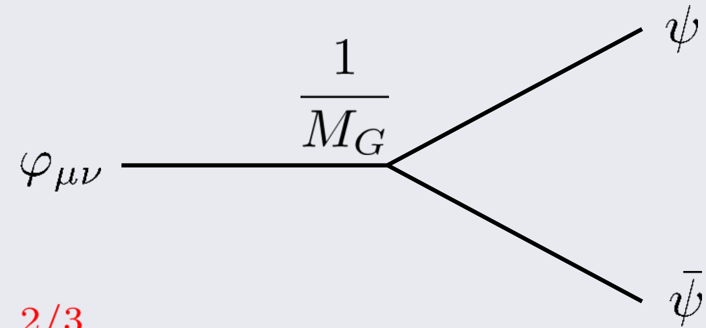
General bounds on massive graviton DM

We can obtain upper bound on graviton mass from the decay rate.

$$S_{\rm massive} = \int d^4x \left[\text{kinetic} + \text{mass} + \frac{1}{2M_G}\varphi_{\mu\nu}T_{\rm m}^{\mu\nu} \right]$$

Total decay rate of massive graviton has to be

$$\Gamma_G \sim 0.1 \frac{m^3}{M_G^2} \ll H_0$$



Upper bound on graviton mass: $m \lesssim 10 \left(\frac{M_G}{M_{\rm pl}} \right)^{2/3} \ \mathrm{MeV}$

Lower bound on graviton mass: $m \gtrsim 10^{-23} \ \mathrm{eV}$

de Broglie wavelength < galaxy scale

Stochastic massive gravitons

KA and S. Mukohyama, arXiv: 1604.06704.

The low frequency projection $\langle\cdots\rangle_{\rm low}$ can be chosen as spacetime average.

$$\langle T_G^{\mu\nu}\rangle_{\rm low} \simeq \langle\varphi^{\alpha\beta}\varphi_{\alpha\beta}\rangle_{\rm low} p^\mu p^\nu$$ = Dark matter

$$(p^\mu p_\nu = -m^2)$$

How to generate massive gravitons?

$$\rightarrow \frac{1}{2M_{\rm pl}} h_{\mu\nu} T_{\rm m}^{\mu\nu} + \frac{1}{2M_G}\varphi_{\mu\nu}T_{\rm m}^{\mu\nu}$$

Gravitons $\xrightarrow{\boxed{\text{massive}}}$ DM

Gravitons $\xrightarrow{\boxed{\text{massless}}}$ GW

$m \sim 10\mathrm{MeV}$ ⟵ 

e.g. LIGO

When GWs are generated, MGs (=DM) are also generated.

Massive gravitons from preheating

Supposing massive gravitons are relativistic at the production,
the present abundance of MG (=DM) is

$$\Omega_G \sim \frac{M_{\rm pl}^2}{M_G^2}\frac{m}{2\pi f}\Omega_{\rm gw}$$

f is the present frequency of GW

We focus on GW to be sensitive in the LIGO range.

e.g. $\rho_*^{1/4} \sim 10^8\,{\rm GeV} \Rightarrow f \sim 40\,{\rm Hz}\,,\; h^2\Omega_{\rm gw} \sim 10^{-9}$

(reheating energy scale)

Dufaux et al. JCAP 0903, 001 (2009)

A set of consistent parameters is

$$m \sim 10\ {\rm MeV}\,, \quad M_G \sim 10^6 M_{\rm pl}$$

Stochastic MG is indeed a candidate of DM!!

originated from preheating

Massive graviton condensate

KA and K. Maeda, arXiv: 1707.05003.

Previous: high-momentum massive gravitons.

We then consider low-momentum gravitons (=coherent gravitons).

Massless: low-momentum = low-frequency ⇒ ill-defined
Massive: low-momentum ≠ low-frequency ⇒ well-defined

We assume the configuration

$$\varphi_{\mu\nu}(t,\mathbf{x}) = \bar{\varphi}_{\mu\nu}(t) + \delta\varphi_{\mu\nu}(t,\mathbf{x})\,, \quad \delta\varphi_{\mu\nu} \ll \bar{\varphi}_{\mu\nu}$$

MG is dominated by the zero momentum mode

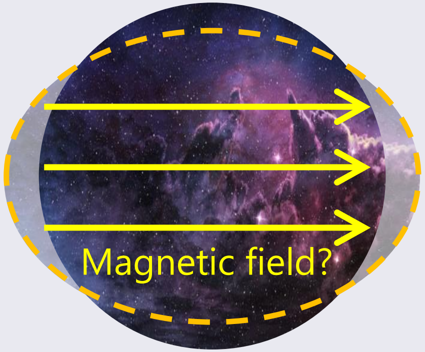
$\langle \cdots \rangle_{\rm low}$ can be chosen as a time average over one coherent oscillation.

NOT spatial average.

→ $\langle T_G^{\mu\nu}(t,\mathbf{x}) \rangle_{\rm low}$ is given by a form of pressureless perfect fluid.

Spacetime anisotropy as dark matter

What is the zero momentum graviton?
→ The homogenous universe = The anisotropic universe



Tiny anisotropy is DM in our scenario.

$$|\varphi_{\mu\nu}/M_G| \sim 10^{-29}\left(\frac{10^{-4}\mathrm{eV}}{m}\right)\left(\frac{M_{\mathrm{pl}}}{M_G}\right)$$

How to produce the anisotropy? Inflation may smooth out it.

Blazar observations implies $10^{-15}\,\mathrm{G} < B_0 \ (< 10^{-9}\,\mathrm{G})$

We find MG can be DM when $m \sim 10^{-4}\left(\frac{10^{-10}\mathrm{G}}{B_0}\right)^8\left(\frac{M_G}{M_{\mathrm{pl}}}\right)^4 \mathrm{eV}$

For example, $B_0 \sim 10^{-12} - 10^{-10}\mathrm{G} \Rightarrow m \sim 10^{7} - 10^{-4}\mathrm{eV}, M_G = M_{\mathrm{pl}}$

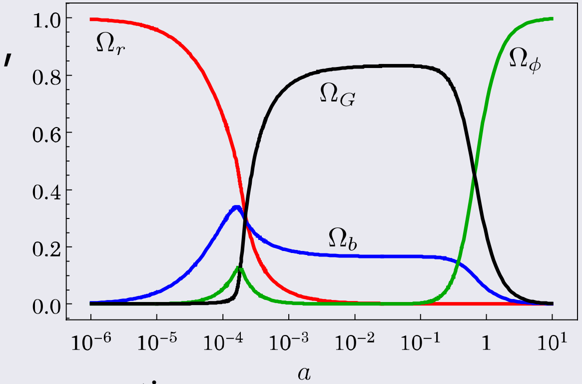
Other options

Non-minimal coupling to dark energy? KA and S. Mukohyama, arXiv: 1708.01969.

If the mass is a function of chameleon field (=DE),

$$m \to m(\phi)$$

→ The present abundance of DM is dynamically adjusted to observed value.



Fuzzy massive graviton?

KA, K. Maeda, Y. Misonoh, and H. Okawa, in preparation.

A light tensor field $m \sim 10^{-22}$ eV can be fuzzy dark matter.

The density profile of MG is the same as the scalar case.

Other scenarios: Thermal production? (when $m \sim$ TeV and $M_G \gtrsim 10^{11} M_{pl}$)

E. Babichev, et al, 2016.

Misalignment mechanism? (= initial anisotropy?)

L. Marzola, M. Raidal, F. R. Urban, 2017.

Summary

Massive graviton is a candidate of dark matter!!

GWs or the magnetic field can carry information about DM (=MG).

Direct detection of graviton mass → consistency relation